HSPF Modeling at the Engineer Research and Development Center

Brian E. Skahill[1]

[1] Research Hydraulic Engineer, Watershed Systems Group, Hydrologic Systems Branch, Coastal and Hydraulics Laboratory, US Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS, (601) 634-3441, Brian.E.Skahill@erdc.usace.army.mil.

Abstract

A widely used regulatory driven tool that is interfaced within the Watershed Modeling System (WMS) is the Hydrological Simulation Program–FORTRAN (HSPF) model. HSPF is a mathematical model developed under U.S. Environmental Protection Agency (EPA) sponsorship for use on digital computers to simulate water quantity and quality processes on a continuous basis in natural and man–made water systems. Despite the widespread use and longevity of HSPF, the abundantly available HSPF model calibration guidance information and support software tools do not support a comprehensive model parameterization effort for a watershed with mixed land uses.

This document describes an issue, related to a recently initiated development effort in the Coastal and Hydraulics Laboratory at the US Army Engineer Research and Development Center (ERDC–CHL), that is fundamental to credible HSPF model simulation support for system–wide ecosystem assessment and recovery. In particular, a need will be demonstrated for credible HSPF model parameterization support for mixed land use systems, a solution presented, and a case study application will provide the proof of concept.

Introduction

The Hydrological Simulation Program–FORTRAN (HSPF) model, a U.S. Environmental Protection Agency (EPA) sponsored, public domain, off–the–shelf, watershed scale hydrologic and water quality simulator, is one tool with a proven track record of supporting system–wide modeling and assessment. ERDC–Vicksburg has utilized the HSPF model to support water quality planning and management, point and nonpoint source pollution analyses, soil erosion and sediment transport studies, and time–series data storage, analysis, and display. In addition, ERDC–Vicksburg has developed and continues to support an interface to the HSPF model in the Watershed Modeling System (WMS). WMS is a graphically based, comprehensive hydrologic modeling environment that has been developed jointly by ERDC–Vicksburg and Brigham Young University to address the needs of hydrologic and water quality computer simulations. The applied research activity briefly described herein is related to ongoing support and enhancements to the HSPF model interface in WMS.

Hydrological Simulation Program–FORTRAN Model

Background

HSPF is a mathematical model developed under EPA sponsorship for use on digital computers to simulate water quantity and quality processes on a continuous basis in natural and man–made water systems. HSPF uses meteorological input data and parameters related to land use patterns, soil characteristics, and agricultural practices to simulate the water quantity and quality processes that occur within a watershed. The HSPF model is generally classified as a lumped parameter model; however, the spatial variability in a watershed can be simulated if the watershed is appropriately divided into land segments which are generally hydrologically homogeneous.

HSPF was first released publicly in 1980, as Release No. 5 (Johanson et al. 1980). Currently, version 12 of HSPF is available as public domain software that can be downloaded from EPA and U.S. Geological Survey (USGS) web sites. Donigian et al. (1995) and USACE (United States Army Corps of Engineers) and USEPA (United States Environmental Protection Agency) (2000) provide graphical and tabular summaries that describe the historical progression of HSPF releases and related development activities. User support, code maintenance, and further refinement and enhancement of the HSPF model are ongoing. Since its original development, the HSPF model has been applied throughout North America and numerous countries and climatic regions around the world. HSPF is the nonpoint source model interfaced within the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system developed by the EPA Office of Water to support Total Maximum Daily Load (TMDL) analysis nationwide.

Model parameterization and uncertainty

A reliable water quality model depends upon a prior satisfactory hydrologic model calibration and validation. For HSPF, there is a fair amount of guidance material and support software that is available, in the public domain, to support a hydrologic model calibration and validation exercise. These include, among others,

1. US EPA BASINS Technical Notes (http://www.epa.gov/ost/basins/bsnsdoc.html#tech),
2. web–based hydrologic calibration guides (http://www.epa.gov/waterscience/ftp/basins/training/tutorial/di.htm, http://www.hydrocomp.com/jour4b.htm),
3. the expert system tool HSPEXP (Lumb et al. 1994),
4. the windows–based HSPF Parameter Database tool HSPFParm (Donigian et al. 1999),
5. past documented HSPF studies, and

6. research articles; for example, Donigian (2002).

Donigian (2002) provided a fairly comprehensive summary of issues related to watershed model calibration and validation based on more than twenty years of experience with the HSPF model.

One of the notable strengths of the HSPF model is its ability to account for the land use distribution within a given modeled watershed. This information, or a blending of this information with other data describing the watershed, serves as a basis for part of the model parameterization process. However, the available guidance information and tools do not support a comprehensive model parameterization effort for a watershed with mixed land uses. For example, the expert system tool HSPEXP does not provide expert advice related to the discernment of parameter differences across land uses. As a result, current practice with HSPF for parameterizing across land uses is a fairly heuristic exercise. Furthermore, the expert system tool HSPEXP does not provide any water quality model parameter estimation support. Clearly, HSPF model parameterization for a typical model deployment is a difficult task alone, despite the availability of support utilities such as HSPFParm (Donigian et al. 1999). The comments provided below, from Munson (1998), clearly underscore this point.

> It quickly became apparent that little data exists to distinguish the hydrologic characteristics among land uses. Indeed, this has always been problematic in HSPF [18]. When setting parameters such as lower zone storage, for example, there is no empirical data to support different LZSN values for different land uses. It makes intuitive sense that wetlands should be able to store more water than forest, which stores more than residential land. However, the magnitudes of these differences can only be guessed at. If the average calibrated value of LZSN is about 15 inches, then any combination of LZSN values should give the same results if they average to fifteen.

Munson's (1998) comments above are also consistent with the National Research Council's (2001) recent recommendation that "guidance/software needs to be developed to support uncertainty analysis" as part of the TMDL modeling process. Coupling of the model–independent parameter estimation tool PEST (Doherty 2002) with HSPF is one path towards a more science based approach to support HSPF model parameter estimation and predictive analysis for mixed land use watersheds.

Model Independent Parameter Estimation

PEST is a public domain model–independent parameter estimator with advanced predictive analysis and regularisation features. It implements a robust implementation of the Gauss–Marquardt–Levenburg method. PEST will adjust model parameters and/or excitations until the fit between model outputs and laboratory or field observations is optimized in the weighted least squares sense. A suite of PEST model utility software is available to be used as part of the calibration and predictive analysis process, some specific to HSPF/PEST linkage and application. PEST, together with its utility software, allows one to incorporate into the parameter estimation process, among others,

1. known/perceived parameter bounds,

2. known/perceived parameter relationships,
3. "volumetric observations" (e.g., over the entire simulation time period, monthly volumetric readings, and/or one or a number of discrete events),
4. one's intuition or indirect knowledge (for example, to determine the relative magnitudes of different flow components (interflow, baseflow, surface runoff)),
5. exceedence–time characteristics, and
6. (prior) information available from outside of the parameter estimation process about what value a parameter should take.

Hence, "reality" and "plausibility" checks can, and should, be implicitly incorporated into the PEST/HSPF parameter estimation process; thus, allowing such an endeavor to remain within the bounds of historical/conventional HSPF model practice.

In addition to some of the above noted capabilities, PEST with HSPF also allows one to assess, the clearly needed (National Research Council 2001), implications of parameter uncertainty (Whittemore and Beebe 2000) on HSPF model predictive uncertainty. In particular, PEST's predictive analysis mode allows one to examine the range of uncertainty of a key HSPF model prediction (e.g., a maximum daily constituent loading, peak discharge, minimum flow, maximum water temperature, minimum DO, …) while maintaining the model in a calibrated (or almost calibrated) state.

Case Study Application – Bautista Creek

In support of supplementary hydrologic studies for a Special Area Management Plan (SAMP), an HSPF model was developed, calibrated, and verified to available flow data for the approximate 120 square kilometer Bautista Creek subwatershed of the San Jacinto river basin in Riverside County, California. Scenario analyses were subsequently performed to simulate the effects of land use change. In particular, the HSPF model was developed and calibrated to recent land surface conditions and scenarios were subsequently performed to simulate a "culturally unaltered" condition and a projected build out (~2020).

The Los Angeles District Corps of Engineers – Regulatory Branch is developing the SAMP for the San Jacinto river basin in Riverside County, California. The purpose of the SAMP is to "develop and implement a watershed–wide aquatic resource management plan and implementation program, which will include preservation, enhancement, and restoration of aquatic resources, while allowing reasonable and responsible economic development and activities within the watershed–wide study area" (Los Angeles District Corps of Engineers 2000).

As part of the SAMP for the San Jacinto river basin, Waters of the United States (WoUS) in the San Jacinto were delineated using a unique planning level delineation procedure (Lichvar 2000). In addition, riparian ecosystems were assessed at the riparian reach spatial scale using indicator based integrity indices of hydrology, water quality, and habitat (Smith 2000). The supplementary hydrologic modeling studies (Smith et al. 2002):

1. provided additional characterization information on baseline conditions of the study area,
2. were used to develop measures or design parameters to minimize impacts to aquatic resources as well as design parameters for the establishment of a successful aquatic reserve system,
3. provided information that could be used by the County of Riverside in the context of flood control, planning, erosion and sediment transport, point and non-point source pollution, Total Maximum Daily Loadings (TMDLs), Best Management Practices (BMPs), as well as other state, local, and federal regulatory compliance programs, and
4. provided an opportunity to evaluate the indicators and indices currently being used to assess riparian ecosystems, all of which are scaled to a reference condition designated as "culturally unaltered".

The Bautista Creek subwatershed of the San Jacinto river basin encompasses approximately 120 square kilometers, and elevations range from about 2,050 m above seal level at the high point on the southeastern edge of the watershed to 508 m at the watershed outlet. Figure 1 shows the relative locations of the San Jacinto river basin and the Bautista Creek subwatershed of the San Jacinto. Land use and land cover is principally shrub and brush; however, small pockets of agricultural activity and urbanization are present in the southeastern section of the watershed and also near the outlet. Table 1 summarizes the land use and land cover distribution in Bautista Creek for the "culturally unaltered", current, and future build out conditions.

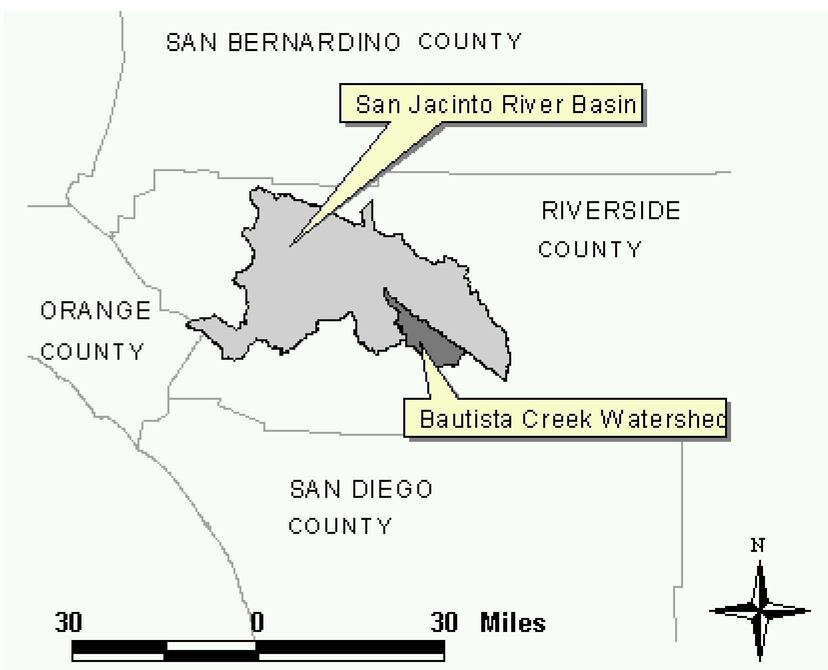

Figure 1. Relative locations of the San Jacinto and Bautista Creek.

Table 1. Land use and land cover distributions in Bautista Creek.

	% of Total Area		
Land Use	Historic	Current	Future
Agriculture	0.00	4.84	4.55
Forests	7.33	7.33	7.33
Grasslands	6.45	1.58	1.52
Riparian	2.45	2.44	2.92
Shrub	83.77	80.89	78.88
Urban	0.00	2.92	4.80

The soils in the subwatershed are SCS hydrologic soil group C soils along the valley slopes and SCS hydrologic soil group A soils on the valley floor. Class A soils possess low runoff potential and consist of deep, well–drained to excessively drained sand and gravel; whereas, class C soils possess a moderate to high runoff potential. It is presumed that precipitation falling on the valley slopes mainly results in overland flow, which infiltrates with direct precipitation through deep, unconsolidated pervious material on the valley floor. The United States Geological Survey (USGS) has operated a streamflow–gaging station on Bautista Creek at the head of a flood channel near Hemet (11070020) since October 1988. Figure 2 shows the location of the USGS streamflow–gaging station 11070020 in addition to the watershed delineation/discretization for Bautista Creek.

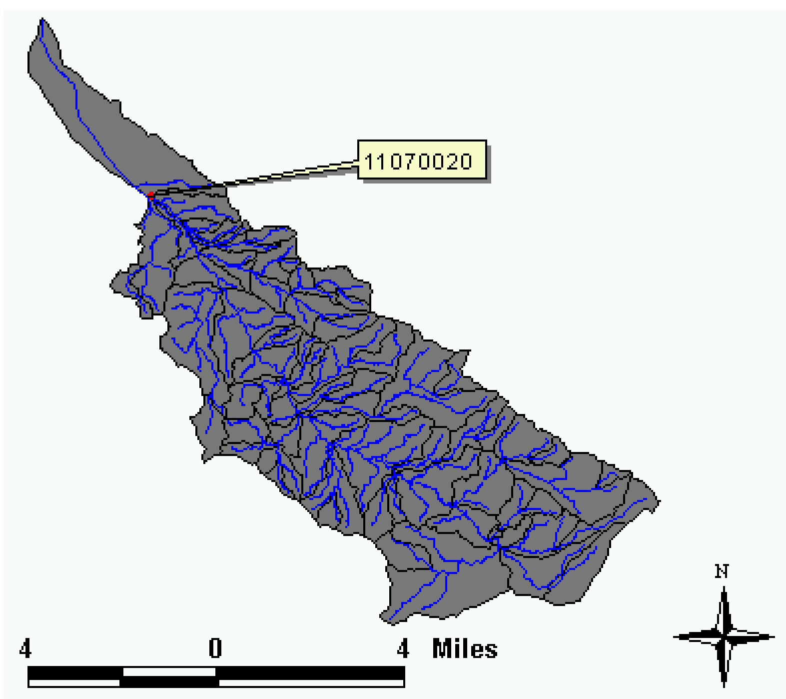

Figure 2. Location of USGS streamflow–gaging station 11070020.

PEST's parameter estimation mode of analysis was applied to an HSPF model of Bautista Creek with the intent to discern parameter differences from the urban land use relative to all of the other modeled land uses within the system for some key HSPF hydrologic model parameters. In addition, PEST's parameter estimation mode of analysis was applied to quantify the streamflow losses along the main stem of Bautista Creek. The parameter estimation process was conducted by comparing three years (1991–1993) of model simulated results against observered daily streamflow data from the USGS streamflow–gaging station on Bautista Creek at the head of the flood channel near Hemet (11070020).

At the end of a PEST parameter estimation run, one obtains a fair amount of information to digest. For example, the number of model parameters considered, a summary of the fixed and tied parameters, a written summary of the parameter estimation process, final optimization results, confidence bounds for the estimated parameters, the computed correlation coefficient for the parameter set that minimizes the objective function, parameter correlations, and parameter sensitivities, among others.

Table 2 presents the optimization results for a PEST parameter estimation run for the HSPF model of Bautista Creek. The estimated parameter values are listed. It is encouraging to note that the *rat parameters listed in Table 2 (i.e., lzsnrat, lsurrat, nsurrat, lzetprat) are all neither zero or one (their upper or lower bound), indicating that PEST was able to discern parameter differences between the urban response relative to the remaining hydrologic response units (other "land uses"). It is also encouraging to see that the PEST parameter estimation process was able to confidently identify a parameter value, x, for quantifying streamflow losses along the main stem of Bautista Creek. You may also see the tied and fixed parameters. Tied parameters are those which "piggy-back" on their parent parameter during the parameter estimation process. PEST does not estimate a value for a tied parameter; rather it adjusts the parameter during the estimation process such that it maintains the same ratio with its parent parameter as that provided through the initial estimates of the respective parameters. Fixed parameters take no part in the parameter estimation process. The fixed parameters listed were fixed based on two previous PEST parameter estimation runs where these parameters were noted to exhibit no sensitivity to the parameter estimation process. Hence, they were simply fixed at their initially estimated values.

Table 2. PEST/HSPF optimization results for Bautista creek model.

OPTIMISATION RESULTS

Adjustable parameters ----->

Parameter	Estimated value	95% percent confidence limits lower limit	upper limit
x	0.634757	0.612868	0.656645
lzsnrat	0.644767	-24.0431	25.3327
lzsn1	12.3644	10.1427	15.0727
lsurrat	0.534488	-3394.28	3395.35
lsur1	700.000	7.000000-298	1.000000+300
deepfr	0.500000	0.247005	1.01213
agwetp	0.200000	1.172201E-03	34.1238
nsurrat	0.537477	-3170.42	3171.49
nsur1	0.500000	5.000000-301	5.000000+299
irctrans	0.190889	-0.155582	0.537361
lzetprat	0.279440	-6.17971	6.73859
lzetp1	0.900000	0.832382	0.973111
infilt	1.000000E-02	4.827482E-03	2.071473E-02
cepsc	6.432573E-02	2.716354E-03	1.52329
retsc	0.129567	9.683998E-27	1.733554E+24

Note: confidence limits provide only an indication of parameter uncertainty.

```
      They rely on a linearity assumption which  may not extend as far in
      parameter space as the confidence limits themselves - see PEST manual.


Tied parameters ----->

Parameter      Estimated value
 uzsn1           1.03036


Fixed parameters ----->

Parameter      Fixed value
 intfwrat       0.500000
 intfw1          1.00000
 ircrat         0.500000
 ilsur           100.000
 insur          6.500000E-02

See file BC2.SEN for parameter sensitivities.
```

Table 3 summarizes the computed parameter sensitivities. Here we clearly see which parameters are most important for the flow model for Bautista Creek. For example, the 3 most sensitive parameters are the lower zone soil storage, the streamflow loss parameter, x, and the parameter defining infiltration losses at the land surface.

Table 3. PEST/HSPF parameter sensitivities Bautista creek model.

Number of observations with non-zero weight = 1132

Parameter name	Group	Current value	Sensitivity	Rel. Sensitivity
x	x	0.634757	3.75605	2.38418
lzsnrat	lzsnrat	0.644767	3.206804E-03	2.067640E-03
lzsn1	lzsn	12.3644	3.10914	3.39572
lsurrat	lsurrat	0.534488	4.908582E-04	2.623580E-04
lsur1	lsur	700.000	0.210207	0.598059
deepfr	deepfr	0.500000	0.248997	7.495562E-02
agwetp	agwetp	0.200000	1.075901E-02	7.520222E-03
nsurrat	nsurrat	0.537477	5.303253E-04	2.850374E-04
nsur1	nsur	0.500000	0.210224	6.328367E-02
irctrans	irctrans	0.190889	7.532260E-02	1.437829E-02
lzetprat	lzetprat	0.279440	5.574380E-03	1.557703E-03
lzetp1	lzetp	0.900000	2.23755	0.102385
infilt	infilt	1.000000E-02	1.04982	2.09964
cepsc	cepsc	6.432573E-02	3.588016E-02	4.275535E-02
retsc	retsc	0.129567	7.834141E-04	6.952832E-04

Representative model results from the scenario simulations are shown in Figures 3 for the main basin outlet of Bautista Creek. Clearly, the results shown in Figure 3 indicate the increased flow volume that can occur as a result of urbanization.

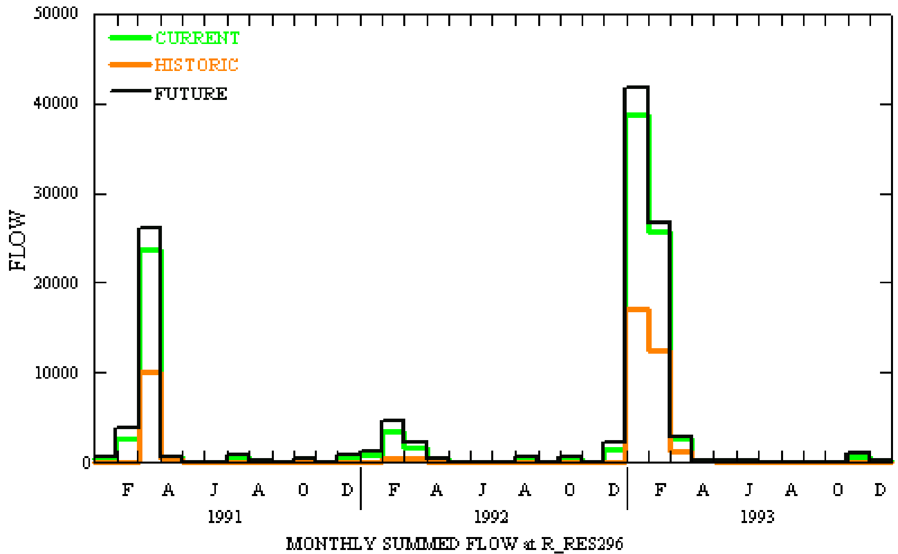

Figure 3. Representative results from the 3 modeled scenarios for the main basin outlet of Bautista Creek.

Summary

Despite twenty years of HSPF model application, there is no guidance information or tools available to support a credible HSPF model parameterization effort across various hydrologic response units (i.e., “land uses”). Clearly, there is a need for tools, and associated guidance information, that can support the credible extraction of HSPF model parameter differences across “land uses” using available data. PEST is such a tool that can do that while remaining within the bounds of historical/conventional HSPF model practice. It can also subsequently look at how parameter uncertainty effects HSPF model uncertainty.

The results presented herein of the preliminary application of PEST to the HSPF model of Bautista Creek were promising in that PEST was able to extract perceived parameter differences across land uses in support of hydrologic simulation. While this specific application of PEST to the HSPF model of Bautista Creek may not be comprehensive relative to the overall objectives of the supplementary studies for the San Jacinto SAMP, it does provide the basis for quantification of the hydrologic impacts of urbanization on the riparian ecosystems. More importantly, this PEST/HSPF application serves as a point of departure for more comprehensive HSPF model simulation support, not only for assessing the impacts of the upland, but also, hopefully, evaluation of alternative recovery scenarios within the assessed as degraded riparian reaches (e.g., revegetation scenarios). Of great interest, is to use the predictive analysis mode of PEST, together with HSPF, to evaluate scenario differences relative to model uncertainty.

While the focus of the case study reported herein was related to the specific theme of the conference (i.e. H&H support of environmental restoration), the issue of credibly parameterizing the HSPF model for mixed land use systems is clearly more broad. Assessing the hydrologic impacts of land use change is currently a rather popular indoor sport.

References

Doherty, J. (2002). "PEST–ASP User's Manual." Watermark Numerical Computing. Brisbane, Australia.

Donigian, A.S. Jr., Bicknell, B.R., and Imhoff, J.C. (1995). "Hydrologic Simulation Program - FORTRAN." *Computer Models of Watershed Hydrology*, edited by V.P. Singh, 395-442, Water Resources Publications, Highlands Ranch, Colorado.

Donigian, A.S. Jr., Imhoff, J.C., and Kittle, Jr., J.L. (1999). "HSPF-Parm: An Interactive Database of HSPF Model Parameters." Version 1.0, EPA-823-R-99-004.

Donigian, A.S. (2002). "WATERSHED MODEL CALIBRATION AND VALIDATION: THE HSPF EXPERIENCE." Water Environment Federation National TMDL Science and Policy 2002 Specialty Conference, November.

Johanson, R.C., Imhoff, J.C., and Davis, H.H. (1980). "User's Manual for the Hydrologic Simulation Program – FORTRAN (HSPF)." EPA-600/9-80-105. U.S. EPA Environmental Research Laboratory, Athens, GA.

Lichvar, R. 2000. Landscape Scale Delineation of Wetlands and Waters of the United States in the San Diego Creek Watershed Orange County, California. Final Report to the U. S. Army Corps of Engineers, Los Angeles District.

Los Angeles District Corps of Engineers. (2000). Draft Scope of Work, Special Area Management Plan, Santa Margarita and San Jacinto Watersheds, Riverside County, California.

Lumb, A.M., McCammon, R.B., and Kittle, Jr., J.L. (1994). "User's Manual for an Expert System (HSPEXP) for Calibration of the Hydrological Simulation Program – Fortran." Water-Resources Investigations Report 94-4168, U.S. GEOLOGICAL SURVEY, Reston, Virginia.

Munson, A.D. (1998). "HSPF Modeling of the Charles River Watershed." M.S. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology.

NRC (National Research Council) (2001). *Assessing the TMDL Approach to Water Quality Management*, *Committee to Assess the Scientific Basis of the Total Maximum Daily Load Approach to Water Pollution Reduction*, Water Science and Technology Board, National Academy Press, Washington, D.C., 2001. (http://www.nap.edu/catalog/10146.html).

Smith, R.D., Kleiss, B.A., Wakeley, J.S., Fischer, R.A., Johnson, B.E., Skahill, B.E., and Downer, C.W. (2002). Scope of Work for Supplemental Technical Studies in the San Jacinto and Santa Margarita Watersheds in Support of the Special Area Management Plan (SAMP). US Army Engineer Research and Development Center, Vicksburg, MS.

USACE (United States Army Corps of Engineers), and USEPA (United States Environmental Protection Agency). (2000). "HSPF/WMS Training Workshop." Vicksburg, MS, September 19 – 21.